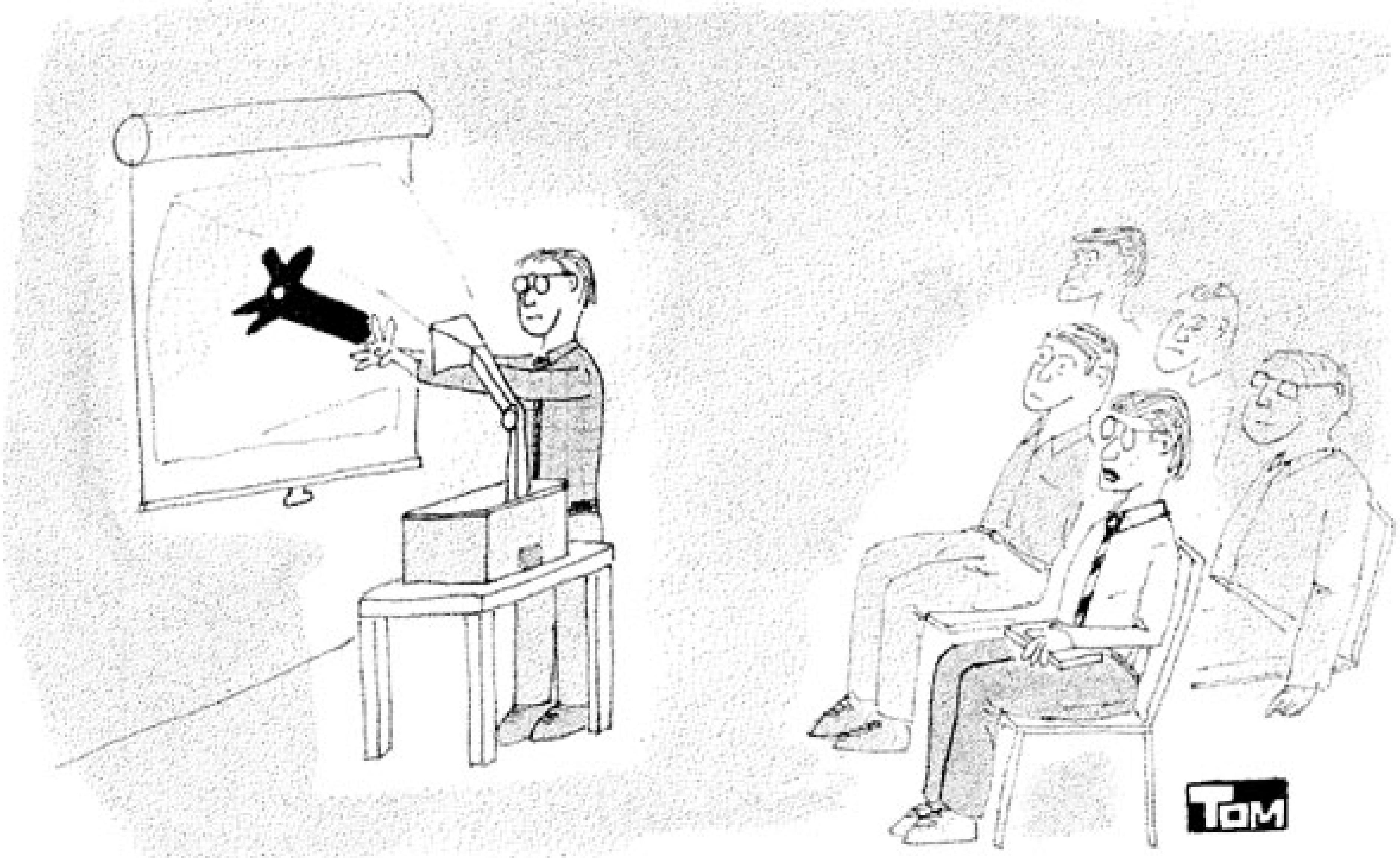
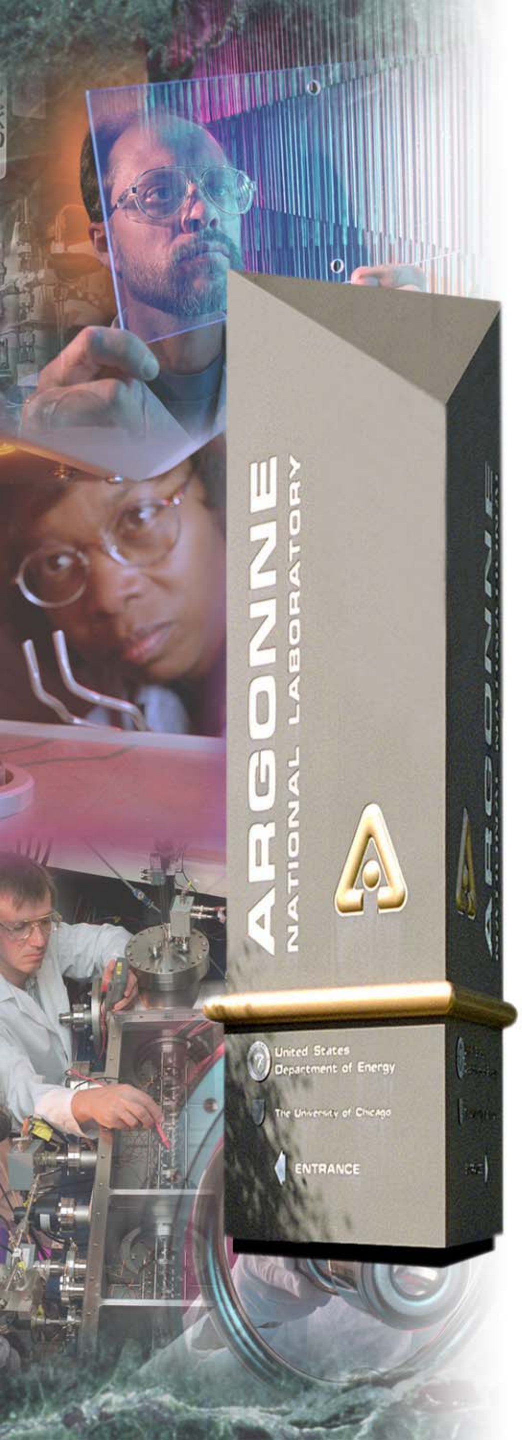
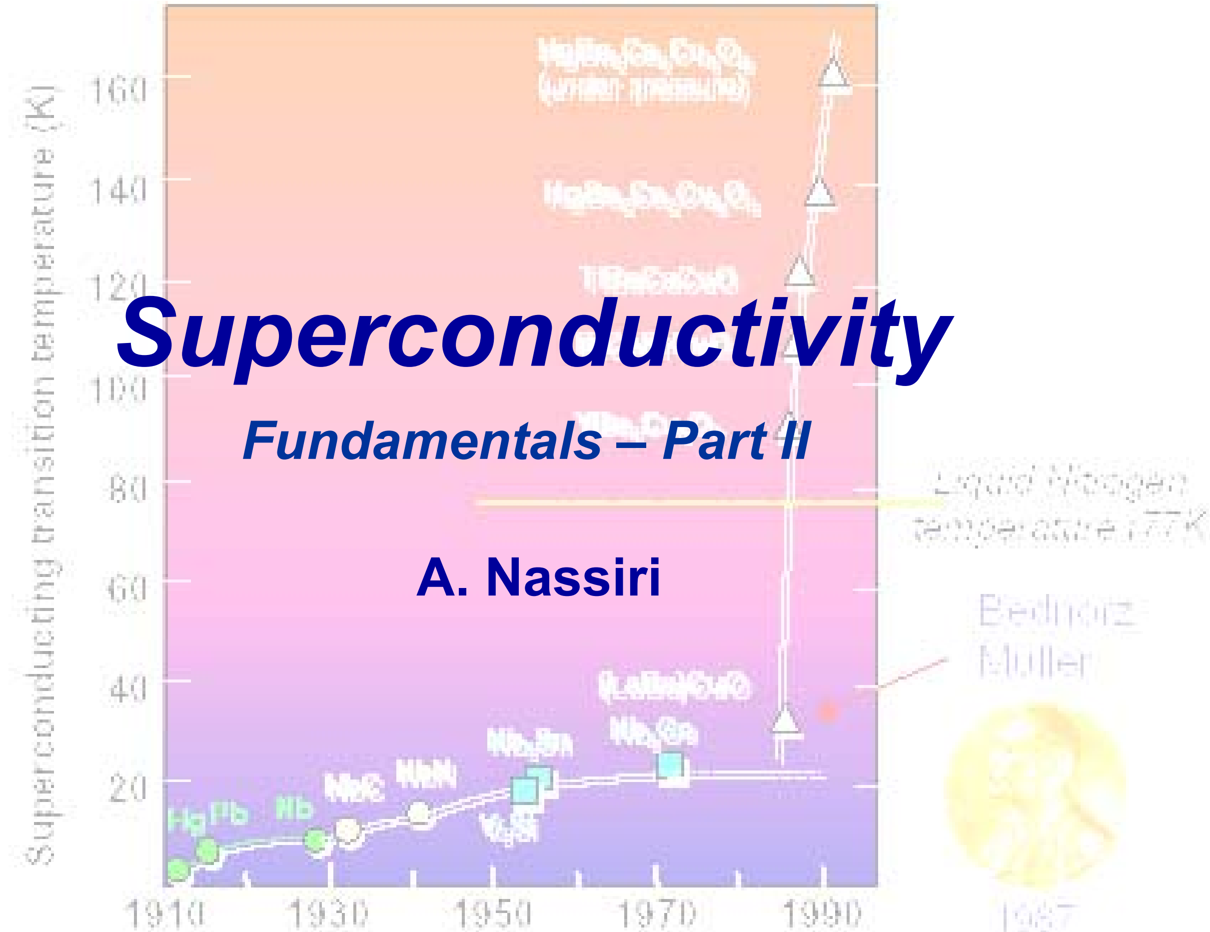


"I WAS HOPING TO SEE MORE EVIDENCE OF THE FLUX-PINNING SITES."





Superconductivity

Fundamentals – Part II

A. Nassiri

Argonne National Laboratory

Thursday, February 17, 2005

Office of Science
U.S. Department of Energy
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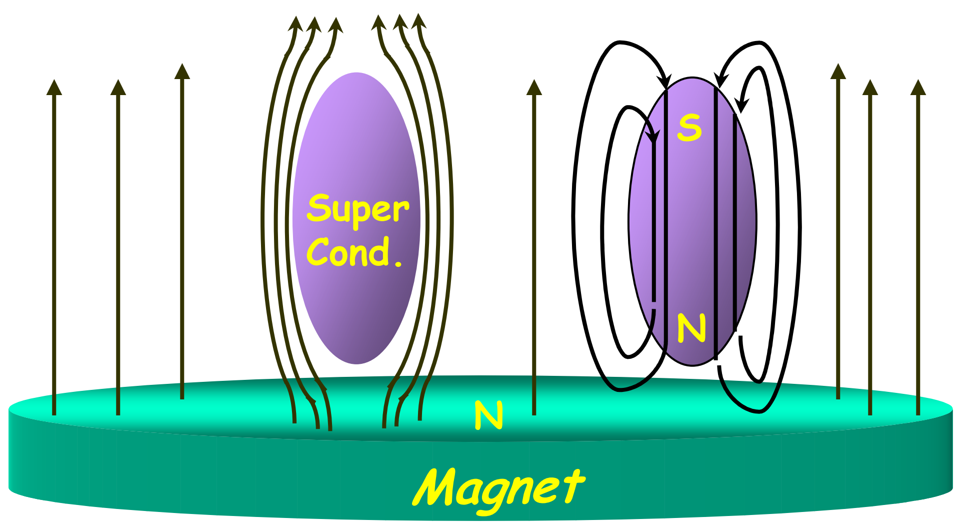
OUTLINE

- Meissner Effect
- Type I superconductor
- Type II superconductor
- Resistivity
- Accelerating gradient limitations
- APS SR RF Options

Properties of Superconductors

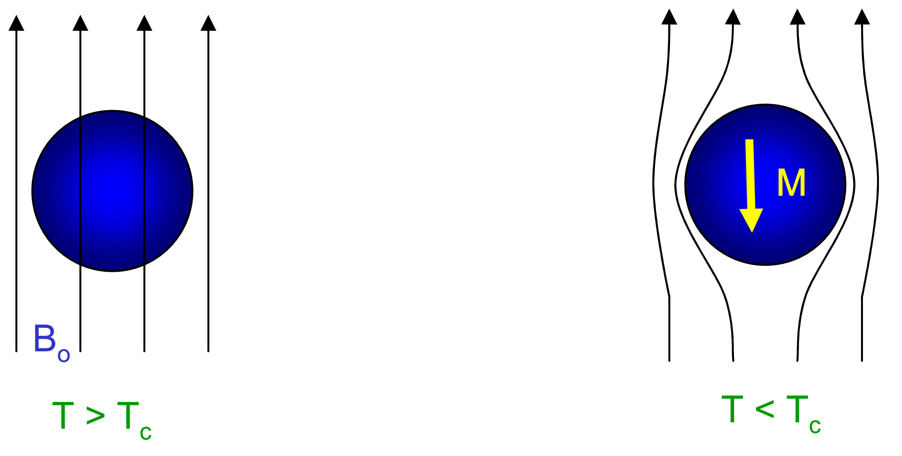
- Zero electrical resistivity (ρ=0) -> persistent current
- Meissner effect
- Critical field, critical current
- Penetration depth, coherent length



Properties of Superconductors

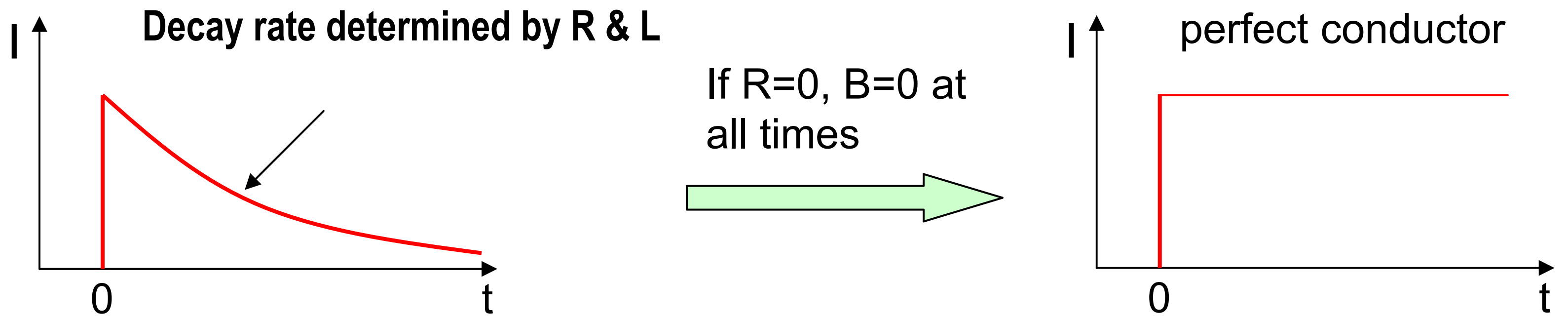
Meissner effect (Meissner & Ochsenfeld – 1933)

Magnetic field is completely expelled by a superconductor (perfect diamagnetism)

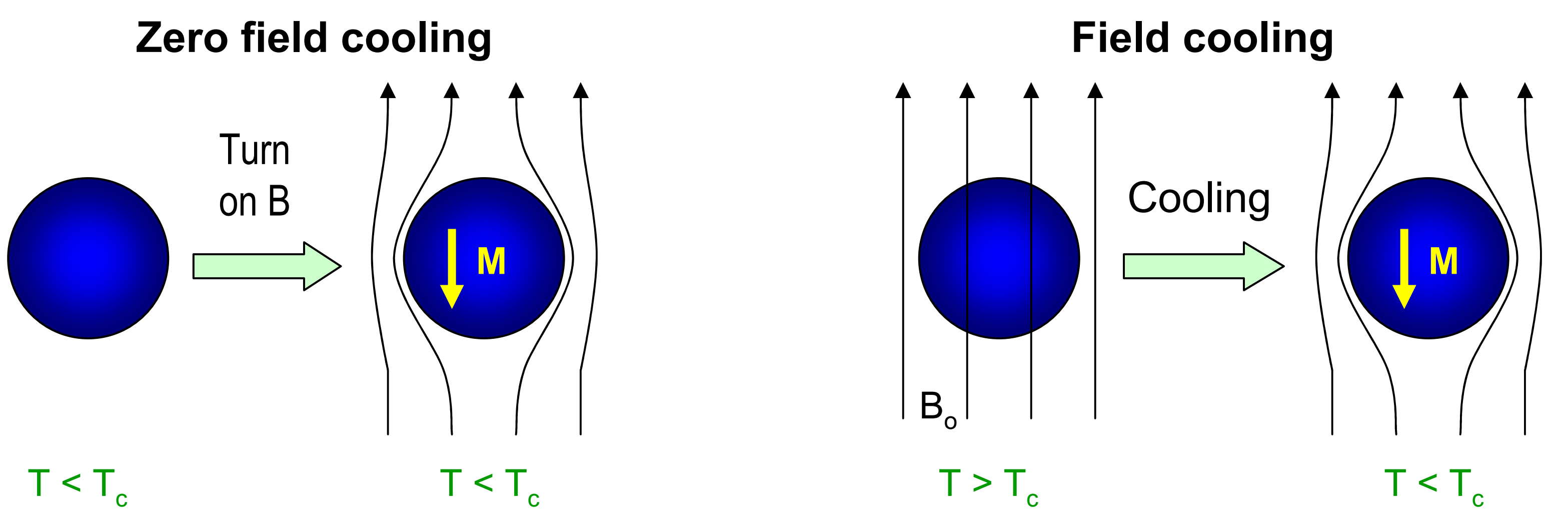


Properties of Superconductors

- Magnetic field is decays. Can be viewed as an RL circuit.

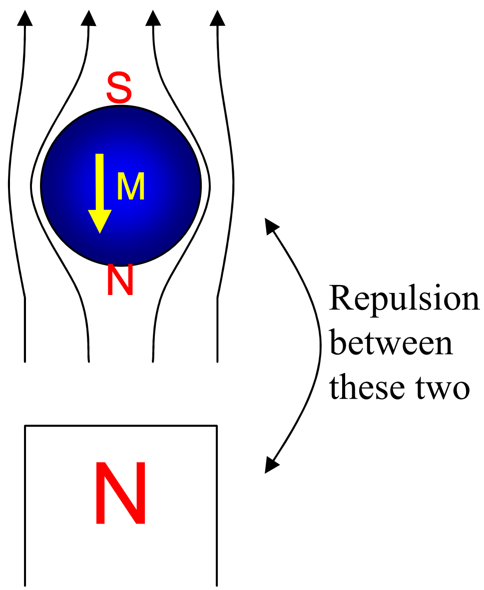


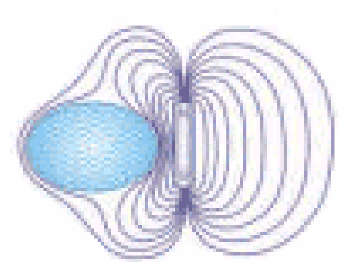
- There is more to superconductor than zero resistance!



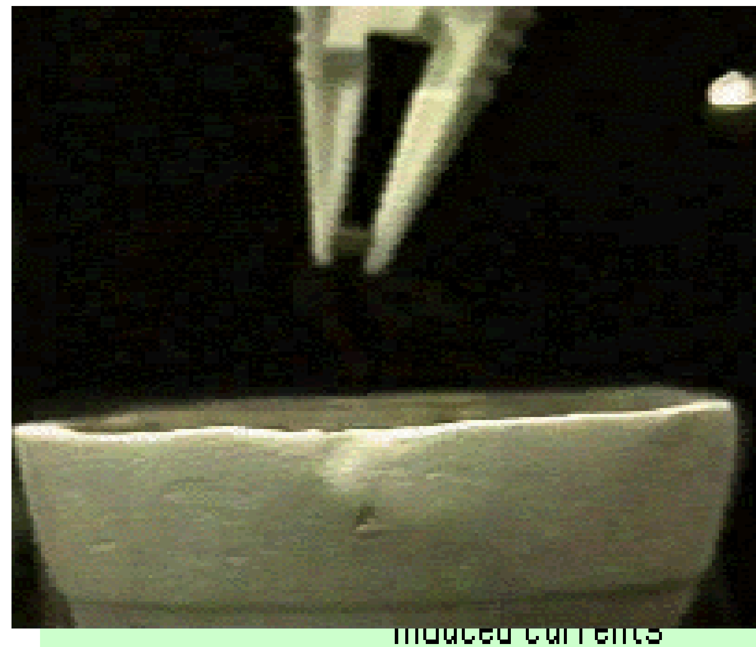
Properties of Superconductors

- Note that just having zero resistance can not explain the field cooling case since there is no change in the external magnetic field upon cooling. Yet magnetic field is still expelled**.**
- Meissner effect is a quantum mechanical effect
- **B** = 0 inside the superconductor and **(j=0)** according to Maxwell's equations. Therefore, there is no current in the superconductor. ⇒ Current flows only on the surface.
- Perfect diamagnetism gives a repulsion force ⇒ Levitation

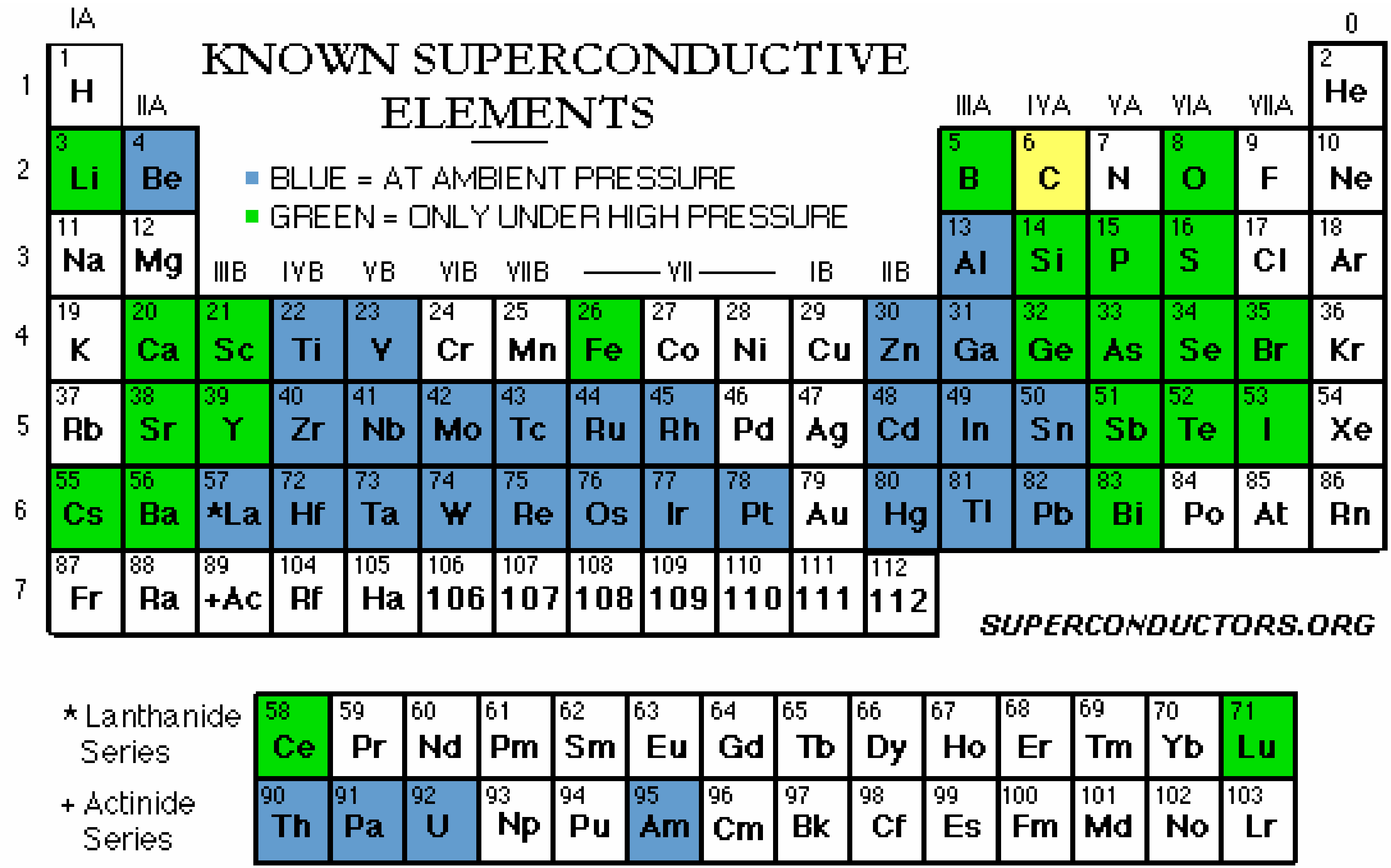




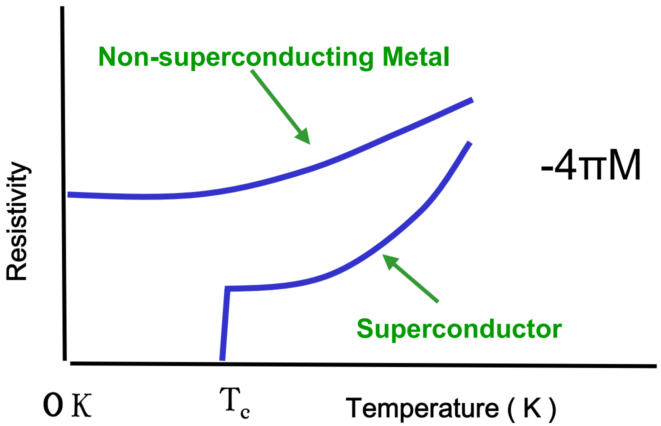
[Flux exclusion](#)
Perfect diamagnetism prevents magnetic field from penetrating a pure superconductor

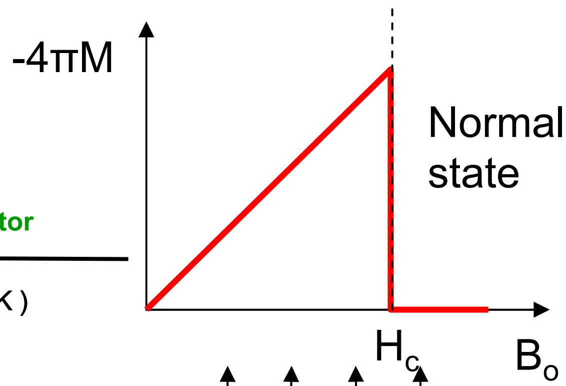


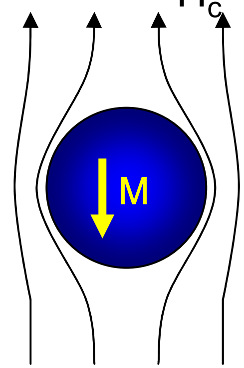
SC periodic table



Type I superconductor





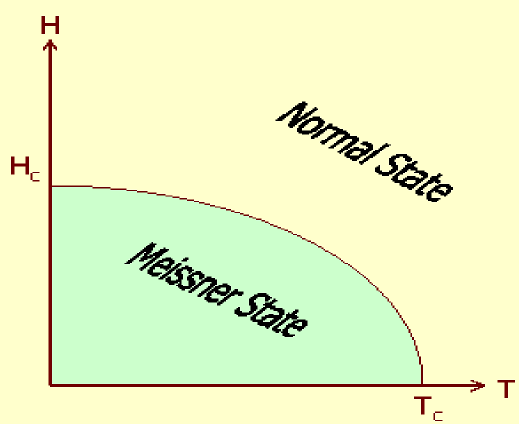


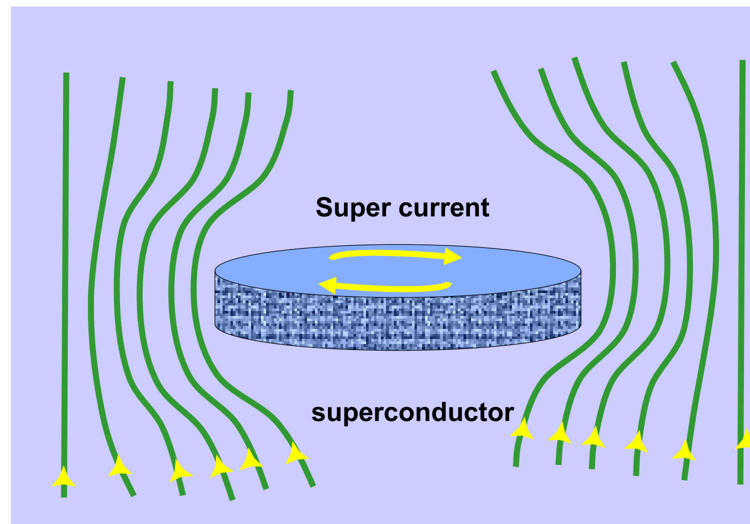
$H < H_c$

Lead (Pb)	7.196 K
Mercury (Hg)	4.47 K
Tin (Sn)	4.15 K
Aluminum (Al)	1.38 K
Gallium (Ga)	1.175 K
Molybdenum (Mo)	1.083 K
Titanium (Ti)	0.49 K
Uranium (U)	0.40 K
Hafnium (Hf)	0.20 K
Iridium (Ir)	0.128 K
Beryllium (Be)	0.1125 K
Tungsten (W)	0.023 K (SRM 768)

Theory: BCS & Ginsburg-Landau

Phase Diagram

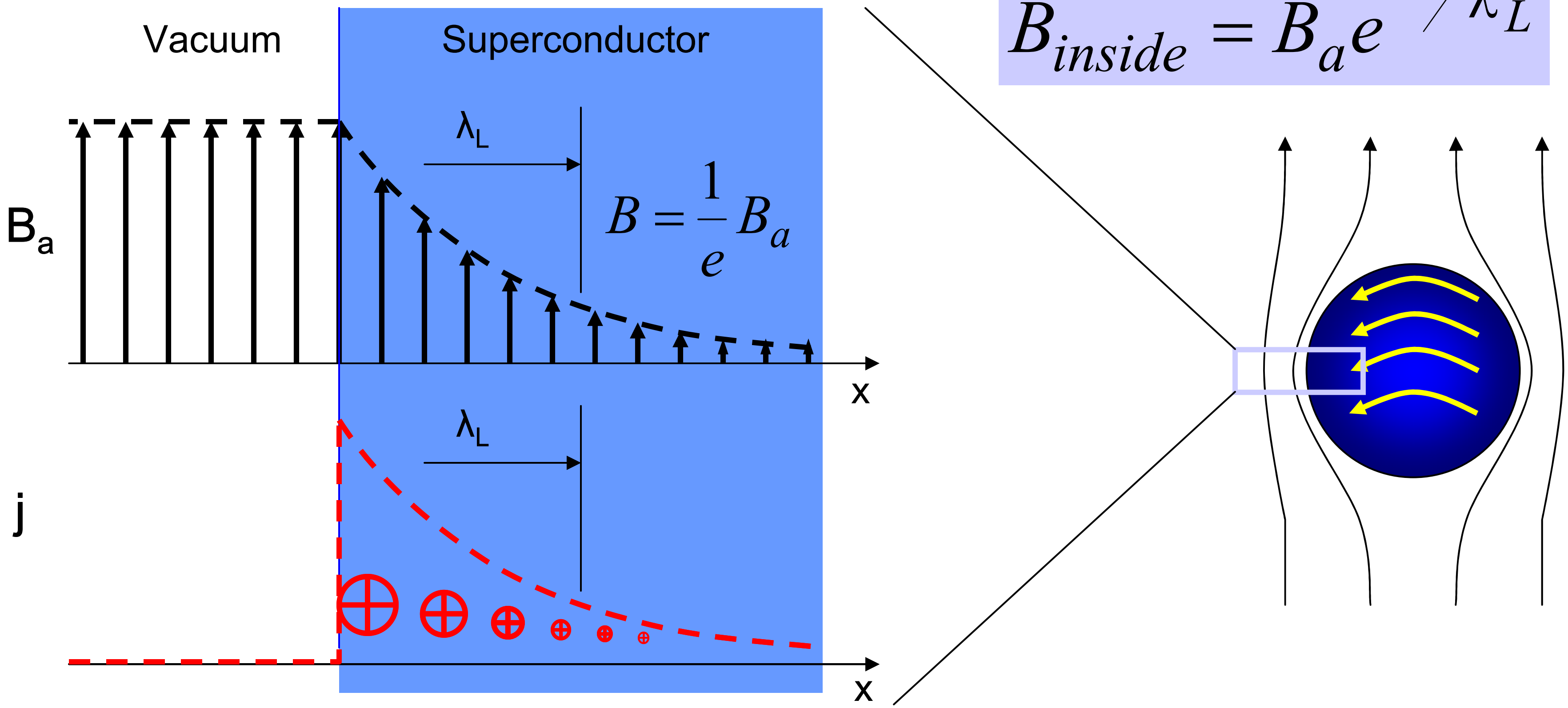




Properties of Superconductors

4. Penetration depth, coherence length

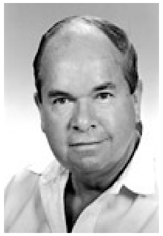
$$B_{inside} = B_a e^{-x/\lambda_L}$$

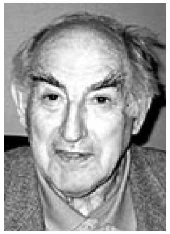


Note that $\lambda_L^2 = \frac{mc^2}{4\pi e^2}\frac{1}{n_s}$ where n_s is the superconducting electron density. If n_s increases, λ_L becomes shorter. In general, pure materials have short λ_L because their n_s is high.

Type II superconductor

Theory: Abrikosov &Ginsburg-Landau


2003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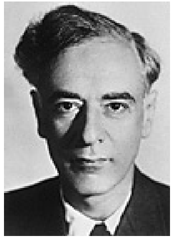
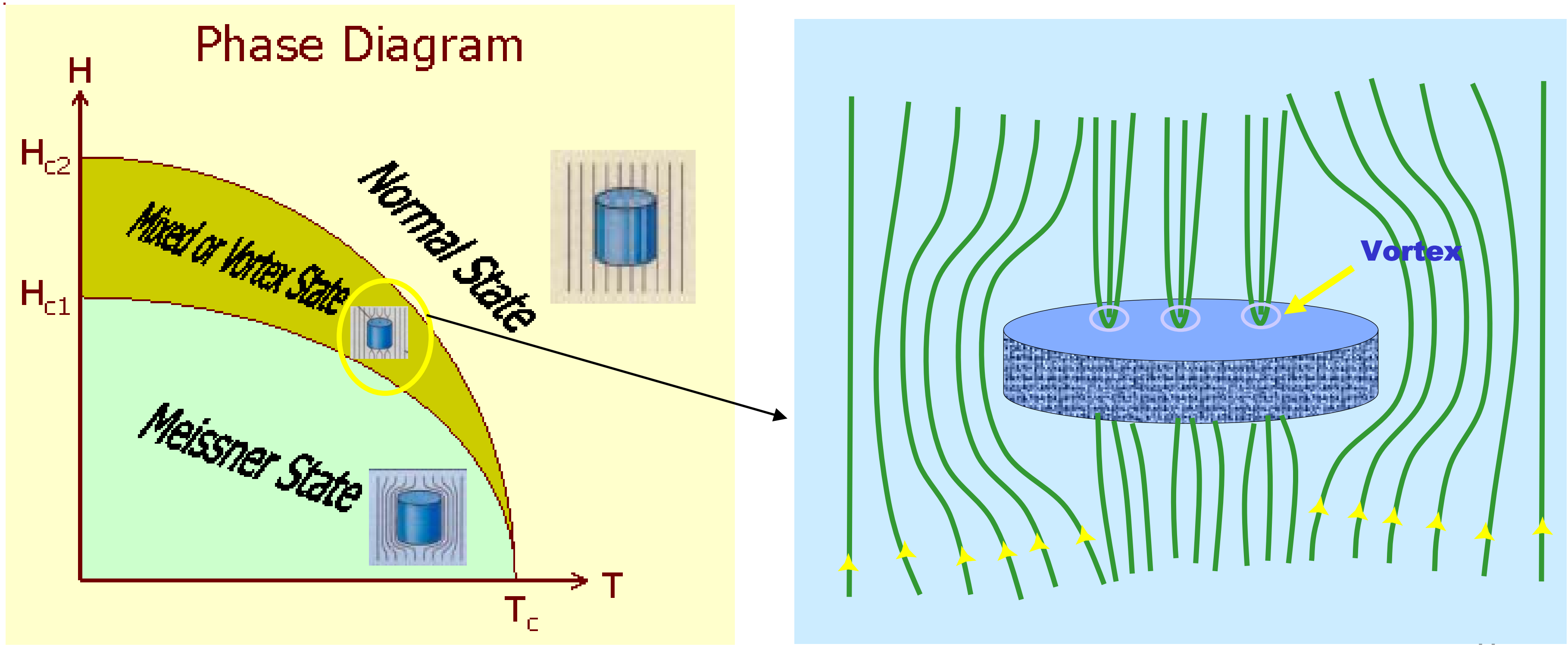
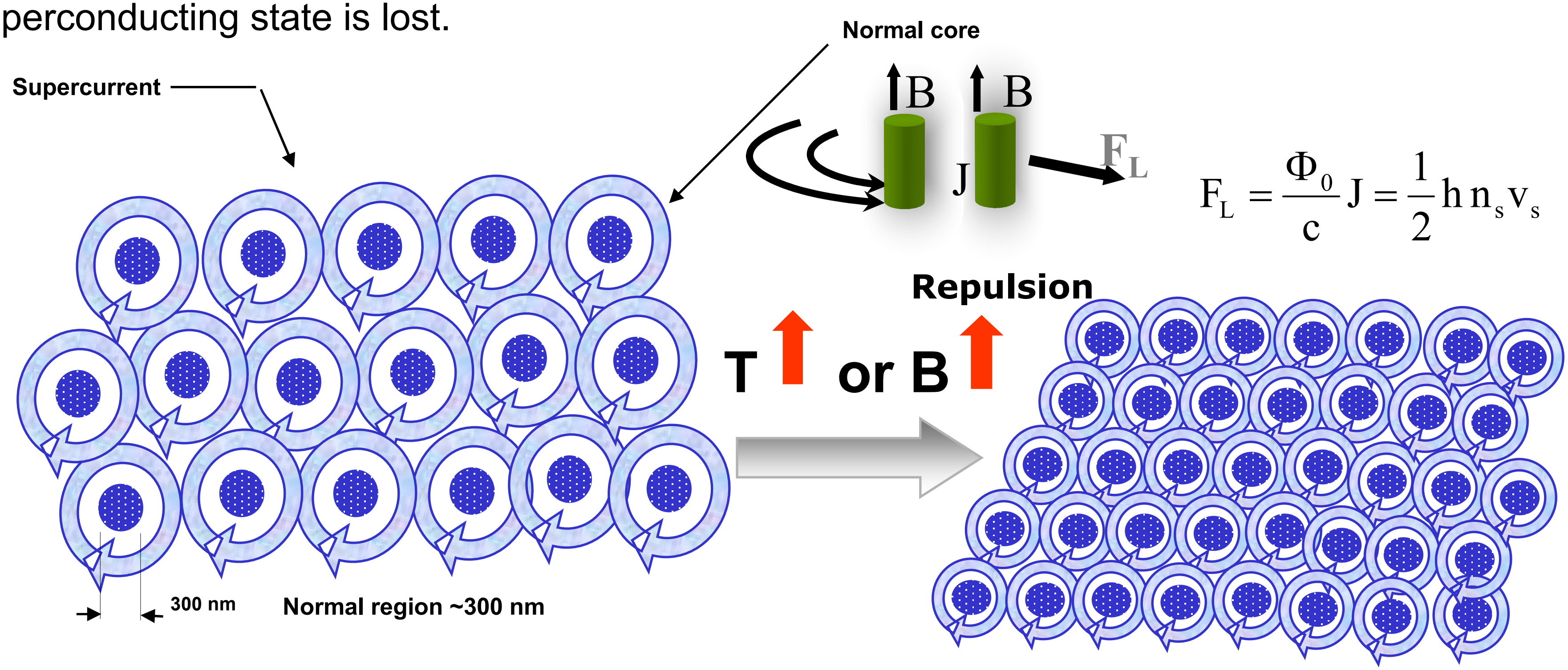

1962



Type II superconductors

Vortex State for Superconductors

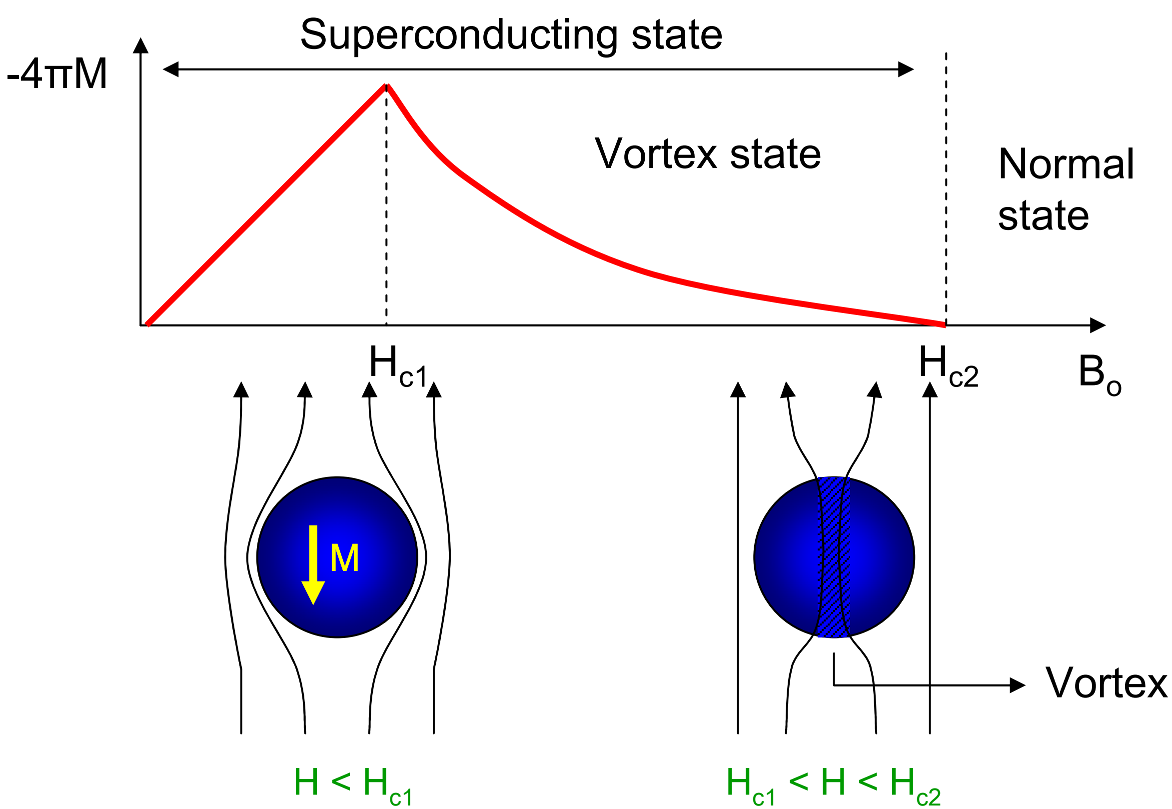
Type II superconductors usually exist in a vortex state with normal cores surrounded by superconducting regions. This allows magnetic field penetration. As their critical temperatures are approached, the normal cores are more closely packed and eventually overlap as the superconducting state is lost.



Properties of Superconductors

3. Critical field (H_c), critical current density (J_c)

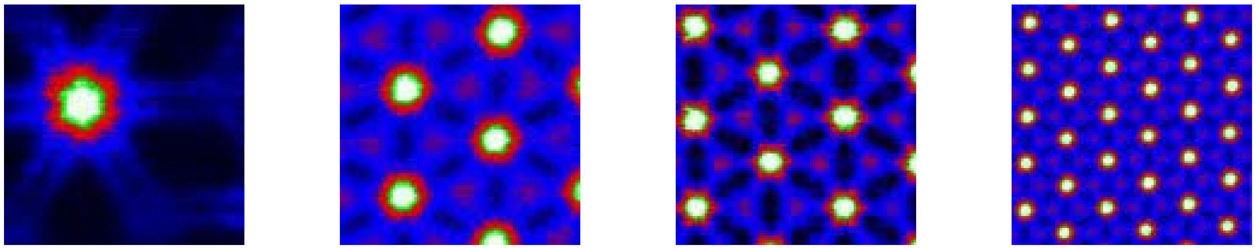
Type II



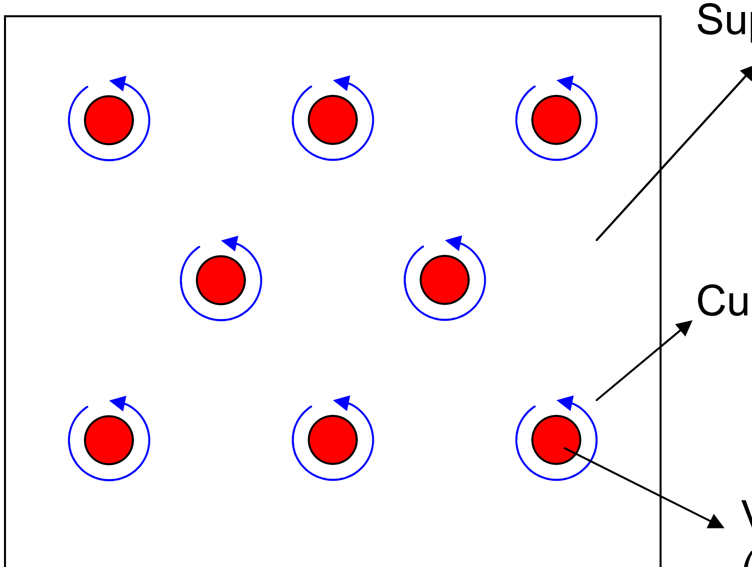
Properties of Superconductors

3. Critical field (H_c), critical current density (J_c)

- Vortex states (STM image on $NbSe_2$)



B = 500 Gauss → 2 T



- Superconductors with high T_c's are type II (Nb, Nb_3Se, Nb_3Ge, …)
- H_{c2} ~ several Tesla
- Important for application

NC vs. SC

Normal Conducting Metal : Skin Depth

$$\delta_s = \sqrt{\frac{2}{\omega * \mu * \sigma}} = \sqrt{\frac{\rho}{\pi * f * \mu}}$$

where: μ = permeability ($4\pi * 10^{-7}$ H/m), note: H = henries = Ω*s

π = pi

δ_s = skin depth (m)

ρ = resistivity (Ω*m)

ω = radian frequency = 2π*f (Hz)

σ = conductivity (mho/m), note: mho [ ] = siemen [S]

Copper at 10 GHz

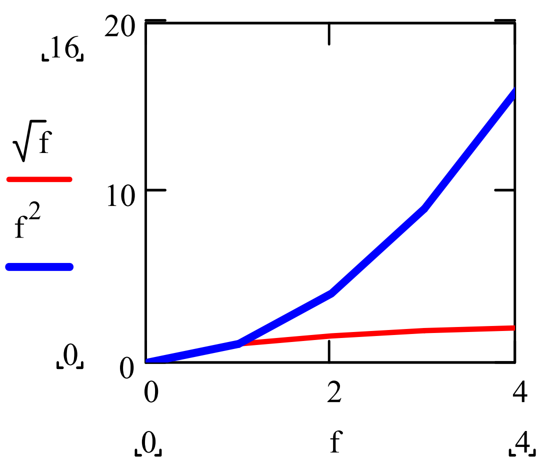
$$\delta_s = \sqrt{\frac{2}{\left(2\pi * 10^{10} \frac{1}{sec}\right) * \left(4\pi * 10^{-7} \frac{H}{m}\right) * \left(5.8 * 10^{7} \frac{mho}{m}\right)}} = \sqrt{\frac{1}{23.2\pi^2 * 10^{10} \frac{H * mho}{m^2 * sec} * \frac{\Omega * sec}{H}}} = 6.61 * 10^{-7}\, m$$

~0.66 μm

Material parameters for some SC

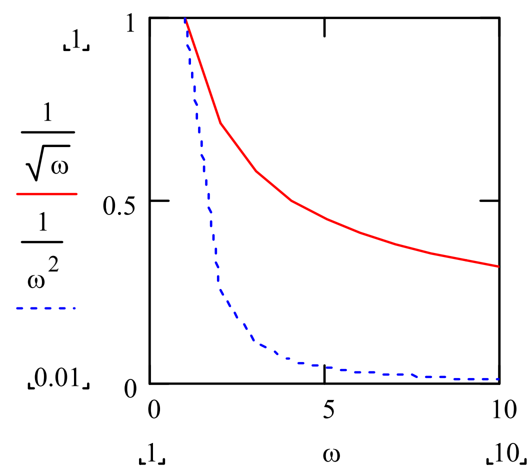
Material	Coherence Length (nm)	London Penetration depth (nm)
Sn	230	34
Al	1600	16
Pb	83	37
Cd	760	110
Nb	38	39

needs only ~40 nm of Nb film!



$$R_s^{SC} \propto f^2$$

$$R_s^{NC} \propto \sqrt{f}$$



$$Q^{NC} \propto \omega^{-1/2}$$

$$Q^{SC} \propto \omega^{-2}$$

Electrical resistivity

- Resistivity ρ is due to scattering
- Scattering rate inversely proportional to the scattering time τ

$$\rho \propto \mathit{scattering\ rate} \propto 1/\tau$$

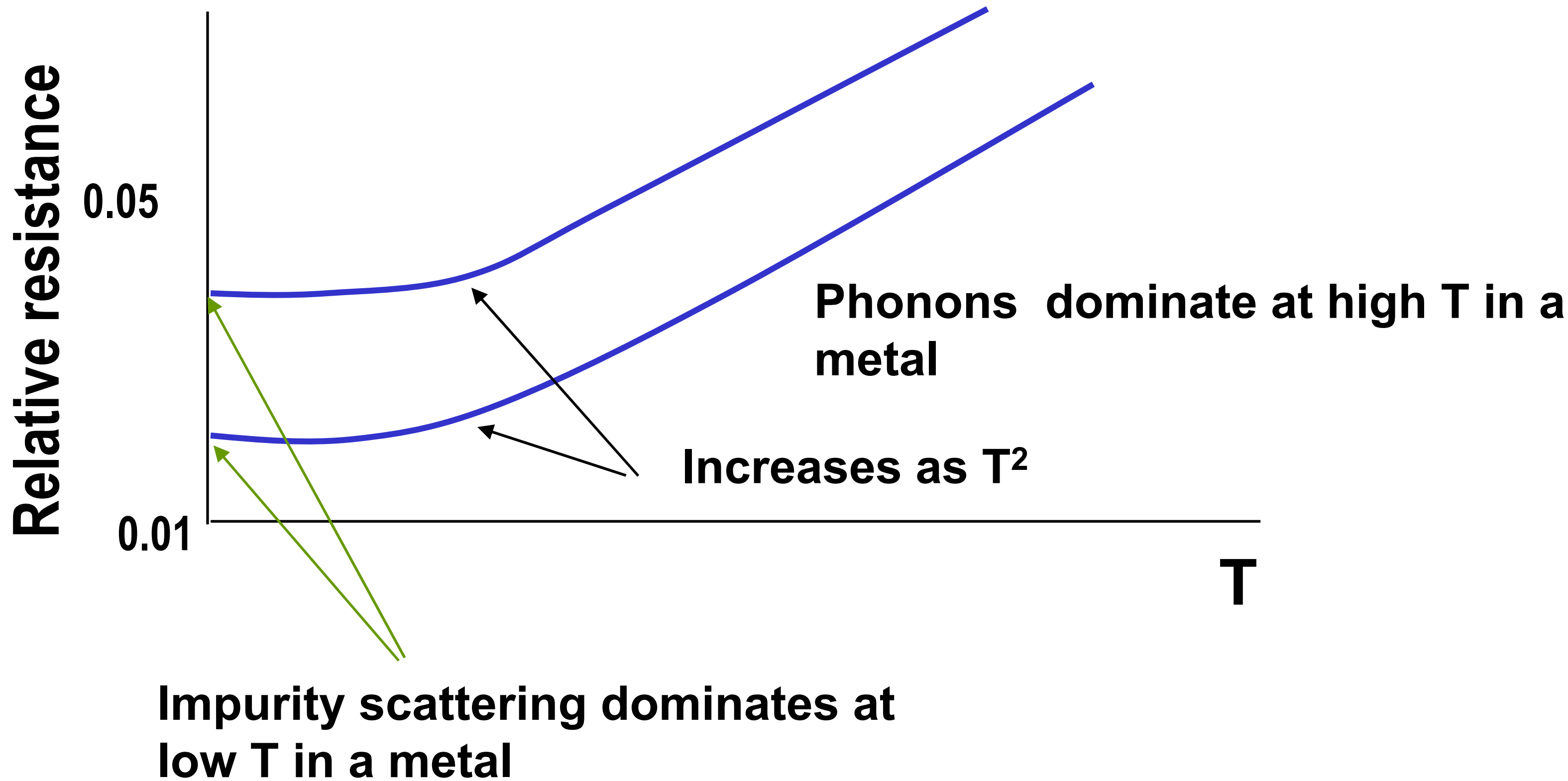
- Matteiesson's rule – scattering rates add

$$\rho = \rho_{vibration} + \rho_{impurity} \propto 1/\tau_{vibration} + 1/\tau_{impurity}$$

Temperature dependent **Temperature independent**

Electrical resistivity

- Consider relative resistivity R(T)/R(300 K)
- Typical behavior (for example potassium)

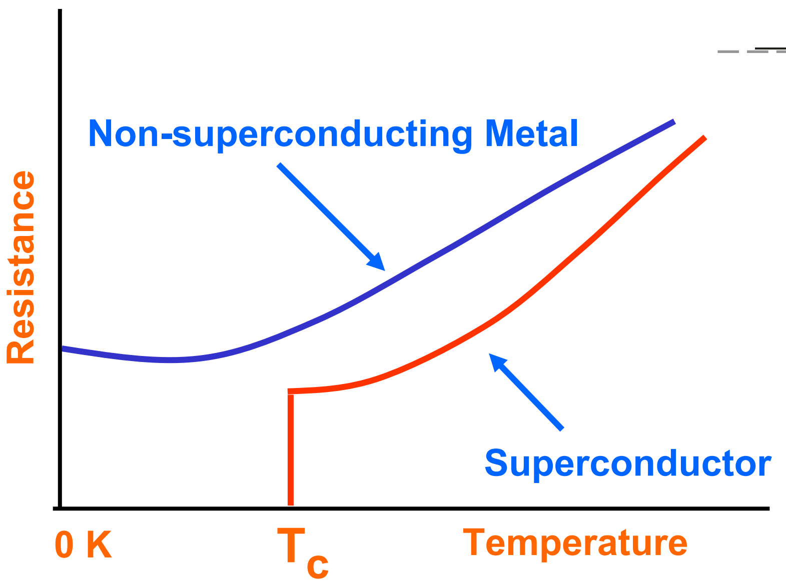


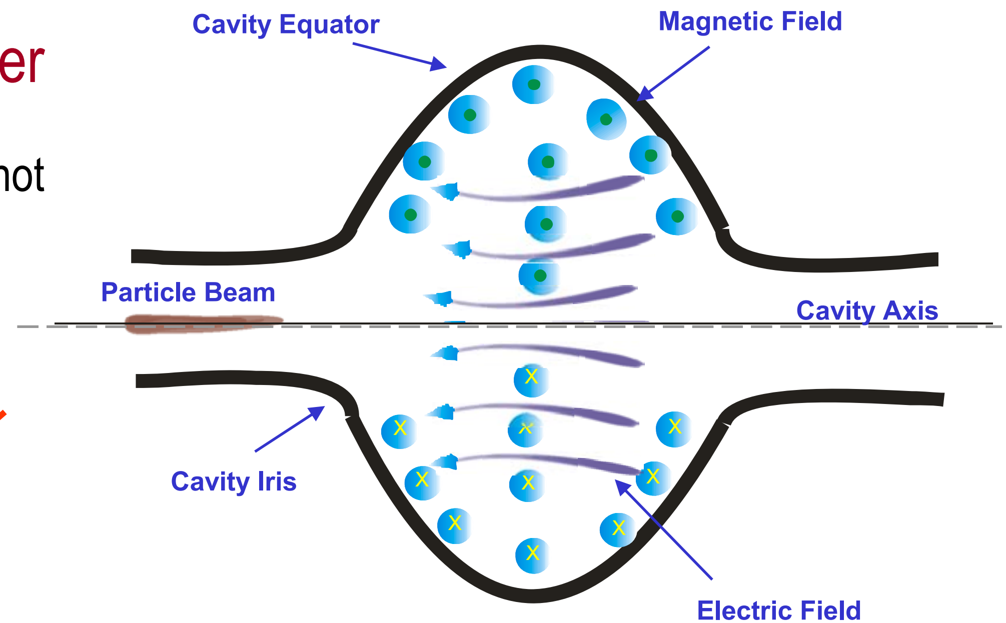
Why use superconducting cavities?

Power dissipation at typical stored energies (few joules, CW)

- Copper cavity several **MW**/meter!
- Niobium cavity watts/meter

Cooling down normal conductors does not help, due to the anomalous skin effect.





Resistivity

$$R_{BCS} \propto f^2 \exp\left(-\frac{\Delta}{KT}\right)$$

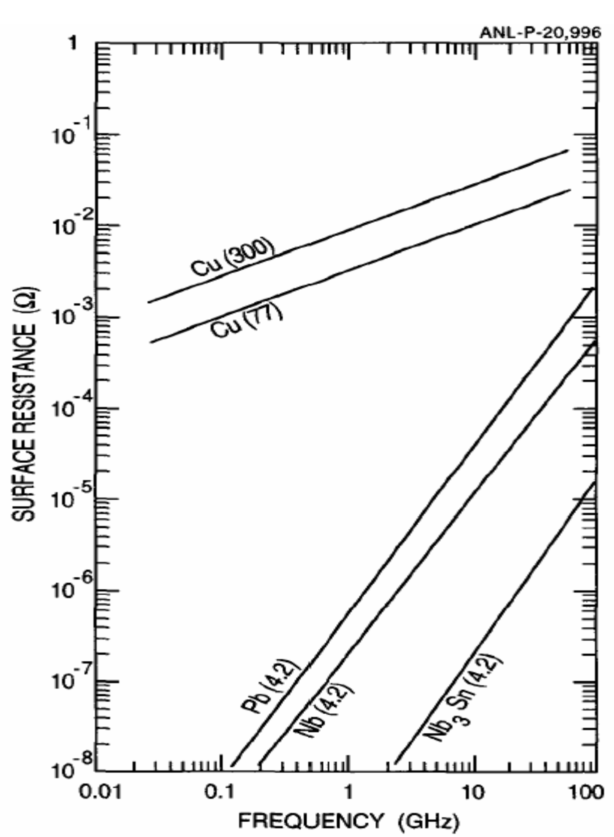
At frequencies above 1 GHz the BCS surface resistance at 4.2 K is so high that the gradient in the cavity will be limited by global thermal heating.

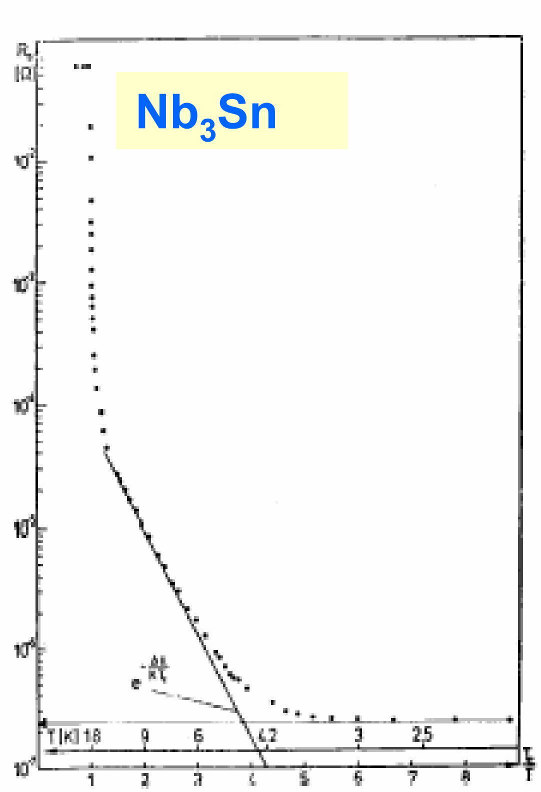
The BCS surface resistance can be lowered by reducing the operating temperature.

1.8 K is chosen in most cases as the operating temperature for cavities in this frequency range to have some safety margin against crossing the point

$$P_{total} = P_{static} + P_{RF} = P_{static} + P_{BCS} + P_{residual}$$

Resistivity





$$R_s = R_{BCS} + R_{res}$$

$$R_{BCS} \propto f^2 \exp\left(-\frac{\Delta}{KT}\right)$$

Definition of unloaded Q:

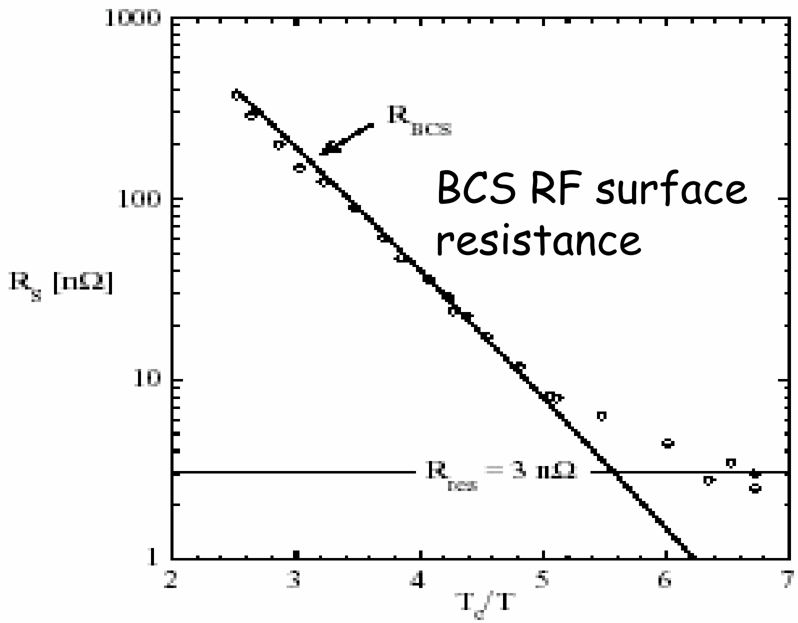
Q_o = (wU/P_d) ~ $(1/R_s)$

U= stored energy

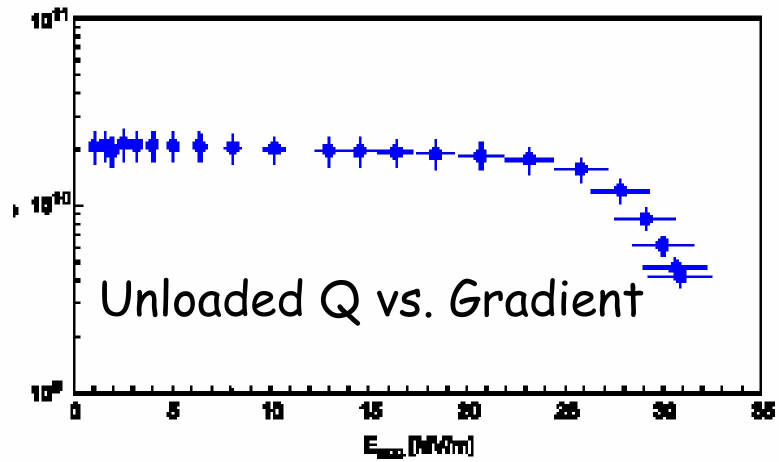
P= power dissipated

R_s=surface resistance

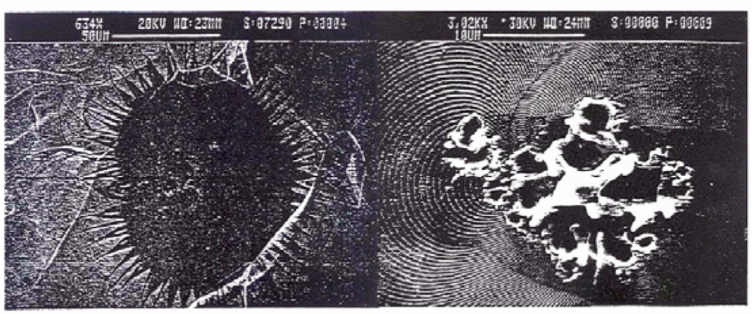
Circumstantial limits



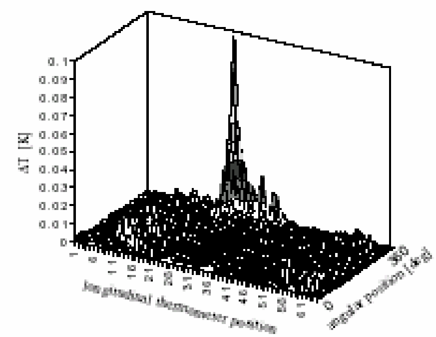
Residual resistance



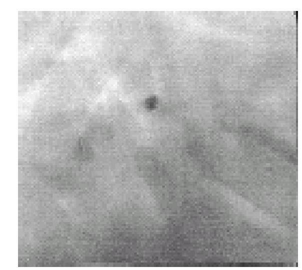
"Field" Emission limitations



- Field emission
- Multipacting



(a)



(b)

- Frozen flux

- Solid materials vs. films

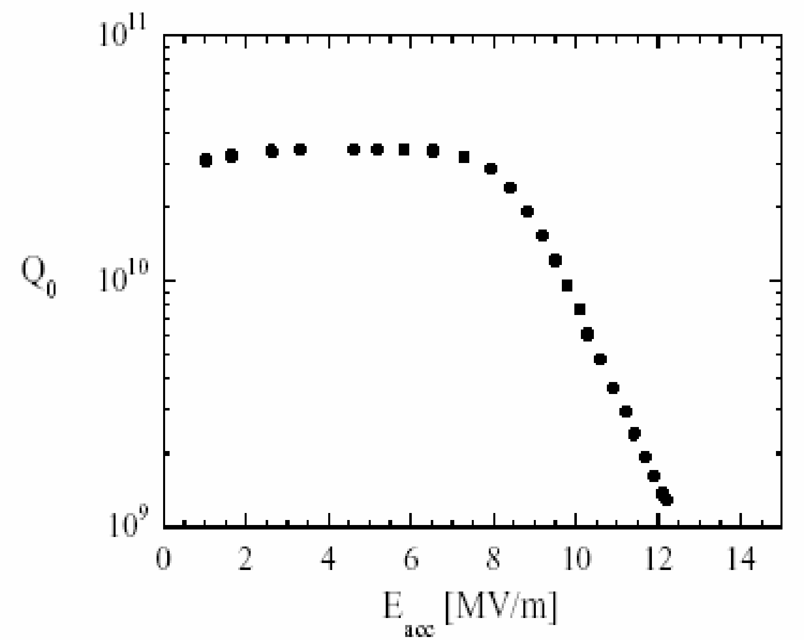
Accelerating Gradient Limitations

Thermal instability (quench)

- avoiding the normal conducting defect by extreme care in preparing and cleaning the cavity surface;
- increase of the thermal conductivity of the superconducting material.

Field emission

- Presence of small particles i=on the surface (dusts)
- Cryo absorption of gases
- Acceleration of dark current



Accelerating Gradient Limitations

Multipacting

- **Resonance multiplication of electrons under the influence of rf field**

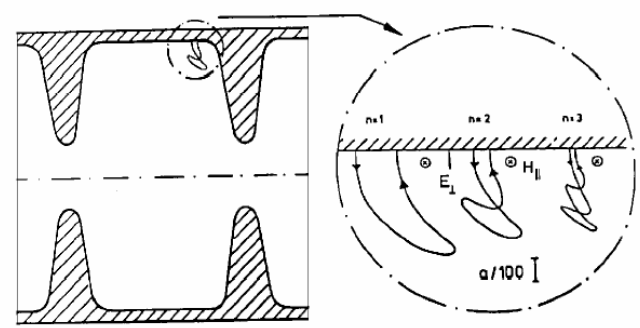
There is a threshold of the field strength in the radiofrequency component. Above this threshold the radiofrequency power can be raised but it has no effect on the stored energy.

The threshold is of sharp nature. The component can be operated below without any sign of unusual behaviour.

The likelihood of multipacting differs for different metals and surface conditions.

Eventually multipacting can be overcome by conditioning. This means that the component behaves normally again after being operated for some time under conditions of multipacting.

Sometimes sparking is observed when operating in the multipacting regime and damage of the component might thereby result.



APS SR (NC)RF

$$P_{total} = P_{beam} + P_{disp} + P_{ol}$$

Ignore this

$$P_{total} = 690kW + \boxed{503kW} = 1193kW$$

This is the problem

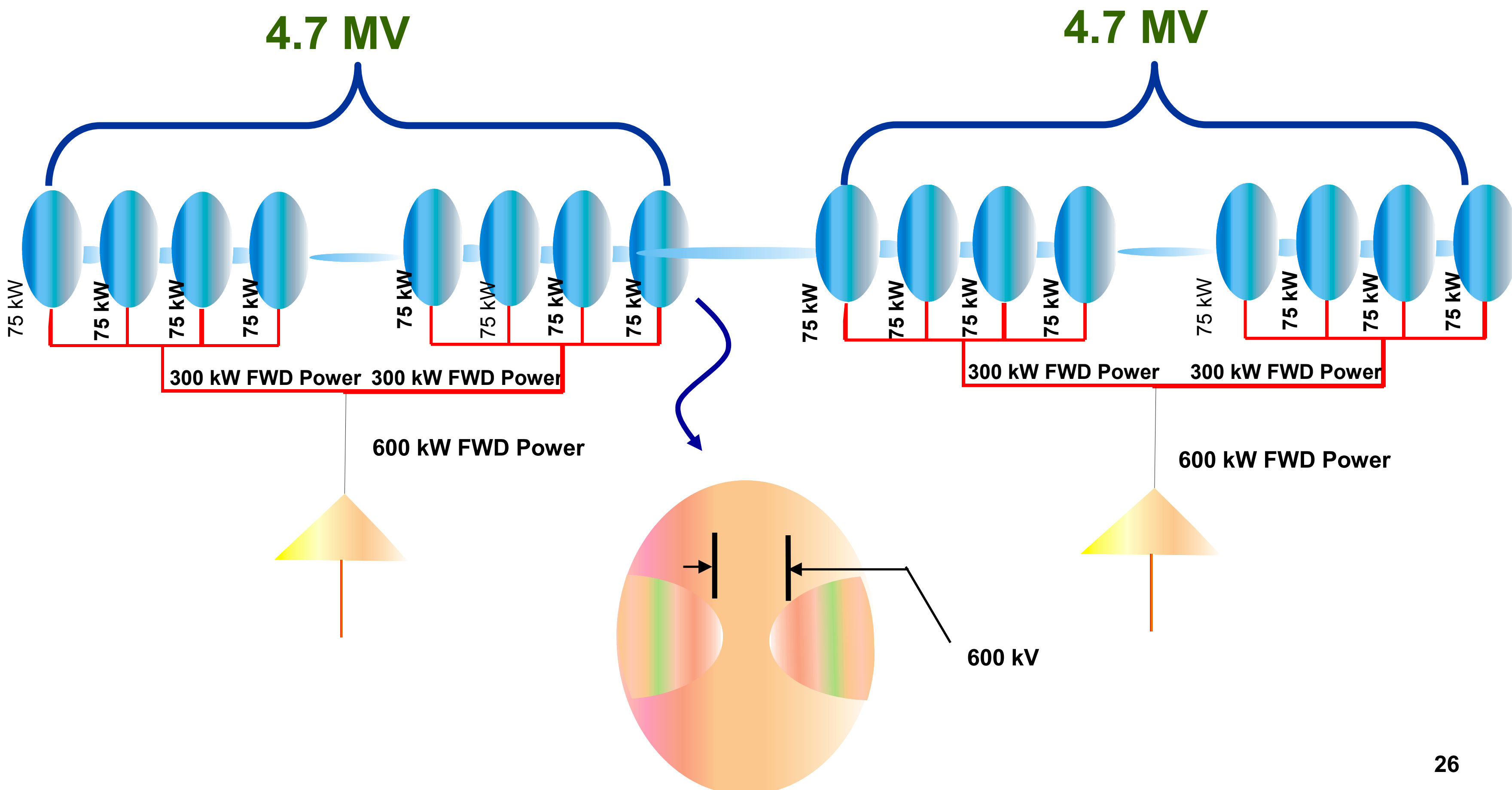
To keep 100 mA, 7 GeV beam circulating in the APS storage ring, we need to provide roughly 1.2 MW CW rf power (@352 MHz):

- **Two klystrons, each producing roughly 600 kW rf power**
- **Each klystron powers eight cavities (2 sectors)**

APS SR (NC)RF

Nominal Operating Parameters:

352 MHz, 100 mA @7 GeV, 9.5 MV

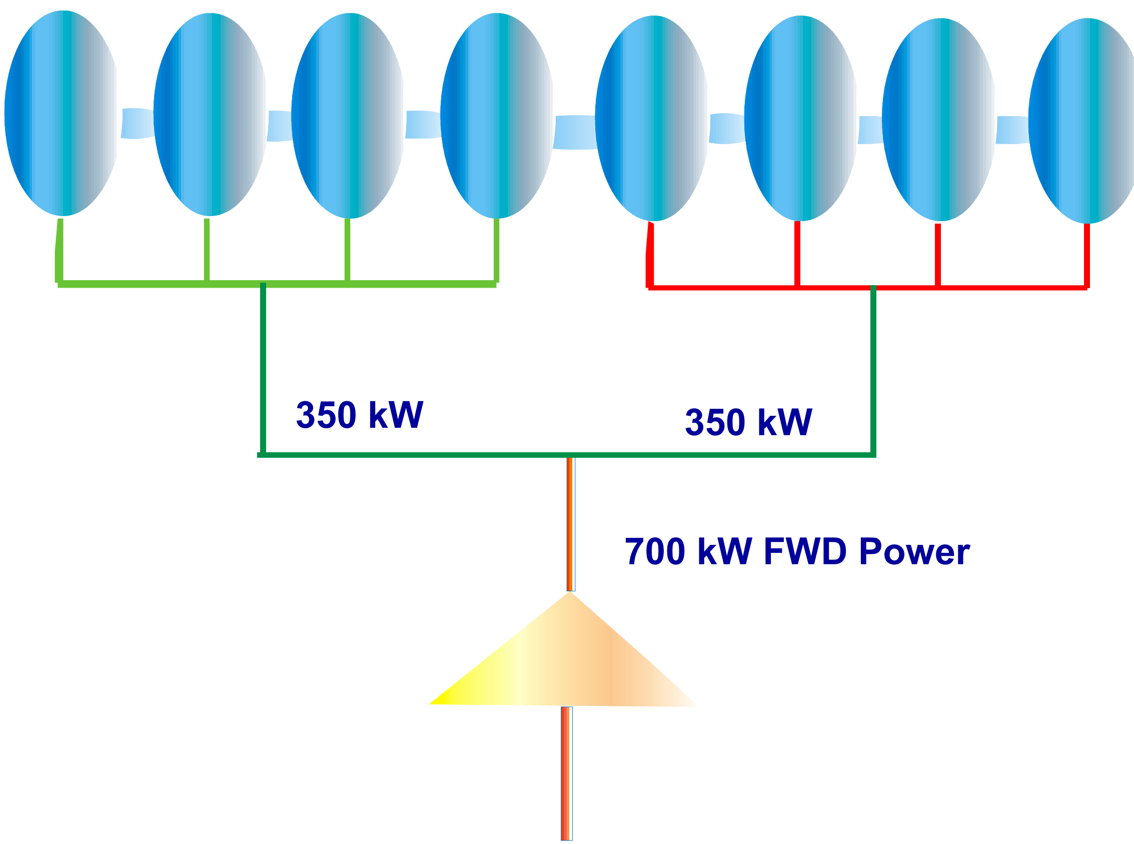


APS SR (SC)RF

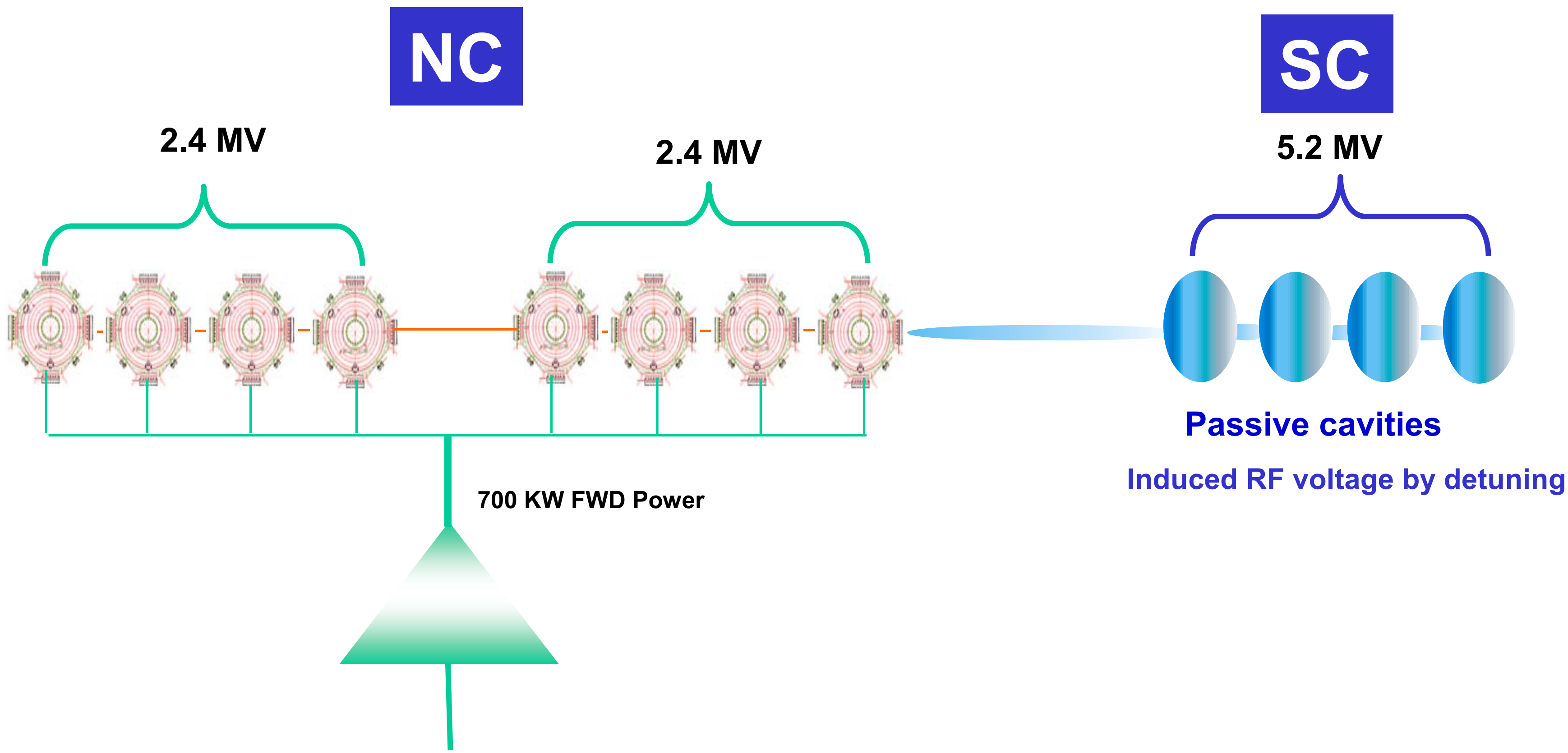
$$P_{total} = P_{beam} + P_{disp} + P_{ol}$$

Ignore this

$$P_{total} = 690kW + 650W = 690.65kW$$



APS SR (Hybrid) RF



Next Lecture

SC RF Cavities   March 2nd

-Design criteria

- frequency
- power consumption
- accelerating gradient

- Geometrical considerations and optimization

- Modeling

- Some examples